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AIRCRAFT MEASUREMENTS OF THE FREQUENCY OF TURBULENCE ENCOUNTERS IN AUSTRALIA

A review and assessment

by

DOUGLAS J. SHERMAN

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SUMMARY

All available aircraft V-g-h measurements of turbulence encounters during routine flying in Australia have been summarised on a common basis. The data are insufficient to determine the Australian gust environment although they are not incompatible with the Royal Aeronautical Society data item ESDU 69023. There are, however, indications that at high altitudes (30,000 ft and above) gusts are encountered more frequently than the data item predicts. This is particularly so for the stronger gusts.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

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16. *ABSTRACT*

All available aircraft V–g–h measurements of turbulence encounters during routine flying in Australia have been summarised on a common basis. The data are insufficient to determine the Australian gust environment although they are not incompatible with the Royal Aeronautical Society data item ESDU 69023. There are, however, indications that at high altitudes (30,000 ft and above) gusts are encountered more frequently than the data item predicts. This is particularly so for the stronger gusts.

CONTENTS

1. INTRODUCTION

A bibliography (Sherman 1981) has recently been prepared listing work related to the occurrence of gusts of aeronautical significance in Australia. Only a small number of investigations give a decomposition by altitude of turbulence encountered in routine flying operations. These investigations are listed in Table 1, and the distances flown in each height band are indicated graphically, in Figure 1, by rectangles whose area is proportional to the distance flown in the height band multiplied by a weighting factor which allows for the relevance of the flying to general Australian aviation. The weighting factors are given in column 6 of Table 1.

The data for three of the programs (NZ Viscount, Comet and 707) are either not available in the published literature or have not been published separately for the Australian region. The data are, however, stored on magnetic tape at the RAE and could probably be obtained in a suitable form. However, Kaynes has indicated, in response to a request for the data, that the age of the magnetic tapes and changes in the RAE Computer System present potential problems for extracting valid data. The data from the Mirage V–g–h program are still being analysed, but they are probably of dubious general application because of the special highly responsive characteristics of fighter aircraft.

Considerably more V–g–h data was acquired from the Boeing 727 aircraft than the 600 hours analysed by Hunter and Fetner (1967). In fact, at DCA's request, NASA fitted V–g–h recorders into a 727 from each fleet (Ansett and TAA) from about 1964 to April 1968, and into a DC-9 from each fleet from about 1966 to 1970. In a paper discussing "initial" data, Hunter (1967) indicated that 533 hours of Ansett 727 data and 346 hours of TAA 727 data had been analysed at that stage. However, the only altitude decomposition available is in Hunter and Fetner's (1967) paper on the first 600 hours. No results are available from the DC-9 program. The complete results of these two programs would be a very significant addition to the total knowledge of the Australian environment, but the analysis does not appear to have been pursued at the time, and as NASA have now closed their V–g–h program it is not certain whether the Australian Department of Transport (which now includes the former DCA) would be able to obtain even the raw data.

The results of the programs for which data are available have been summarised in the Appendix. In all this data there are really only three major programs covering the Australian area. These are the Qantas Super Constellation flights, mainly around 15,000 ft, the Viscount flights, mainly around 20,000 ft, and the Boeing 727 flights, which were mainly around 35,000 ft.

2. THE VARIATION OF TURBULENCE WITH ALTITUDE

One of the well recognised design codes for gust loads has been produced by the Royal Aeronautical Society of London as the ESDU data item 69023. We will compare the available Australian design data with the design curves shown in that data item. The distance between gusts which exceed 3 m/s is conventionally denoted ℓ_{10}.*

Figures 2 and 3 show the variation of ℓ_{10} with altitude, for the data listed in Table 1, and on the same graphs the design curves from Figures 1 and 2 of the ESDU data item are shown. (In these and the later figures the octagons around each data point have an area proportional

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* Following present aeronautical usage we have retained the imperial units of nautical miles for horizontal distance and feet for altitude. Gust velocities have been converted from ft/s to m/s using the approximate conversion factor 0·3 ms = 1 ft/s. Following the ESDU data item we have retained the nomenclature (ℓ_{10} rather than ℓ_3) for the distance between gusts which exceed 3 m/s (i.e. 10 ft/s).

TABLE 1

Aircraft Measurements of Turbulence in the Australian Region

1 Aircraft	2 Region	3 Altitude (× 1000 ft)	4 Hours	5 Nautical miles (× 1000)	6 Weighting Factor (for relevance to Australia)	7 Reference
Bristol Freighter	South-eastern Australia	0–10	95	15	1·0	Baum & Hooke (1953)
Viscount	Australia	17–22	88	24	1·0	Bacon (1956)
Bristol Freighter	New Zealand	0–10	575	80	0·7	Heath-Smith (1958)
Super Constellation	Australia	0–21·5	445	106	1·0	Heath-Smith (1959)
Super Constellation	Indian Ocean	0–21·5	472	110	0·3	Heath-Smith (1959)
Super Constellation	Far East	0–21·5	733	169	0·3	Heath-Smith (1959)
Super Constellation	Pacific Ocean	0–21·5	1255	289	0·3	Heath-Smith (1959)
Viscount	Australia	0–27·5	686	185	1·0	Visick (1965)
Canberra (TOPCAT)	Flinders Ranges, SA	36	30	7	1·0	Wells (1966)
Boeing 727	Australia	0–37·5	600	250	1·0	Hunter & Fetner (1967)
Data not yet published or not published separately for Australia						
Comet 4	Australia	0–42	~120	48	1·0	Kaynes (1971)
Viscount	New Zealand		~600	177	0·7	Kaynes (1972)
Boeing 707	Australia		~90	36	1·0	Kaynes (1974)
Mirage	Williamtown, NSW	0–40	<600	<180	1·0	Unpublished
Following data may never be available unless special efforts are made						
Boeing 727	Australia		>279		1·0	Hunter (1967); also DOT (Australia) and NASA
DC9	Australia		Unknown, but probably about 1000 h		1·0	DOT (Australia) and NASA

to the distance flown in the altitude band, multiplied by the appropriate weighting factor from column 6 of Table 1.) At low altitudes (below 5000 ft) there is insufficient data to make any conclusive statement. The Australian Bristol Freighter data indicate a low incidence of turbulence, which might be expected since much of the flying was over the sea (across Bass Strait). Likewise the New Zealand Bristol Freighter data for the low altitudes indicate low turbulence, and much of this data represents flying across Cook Strait. The medium altitude turbulence tends to average out near the design curve; the Viscount data being milder than would be expected, given the fact that the aircraft were not equipped with radar, and the Super Constellation data for the Australian region being more severe than would be expected. At high altitudes (around 35,000 ft) the TAA 727 data is a little less severe than the appropriate design curve (for aircraft with cloud warning radar) whilst the Ansett data is much more severe than even the design curve for aircraft without radar. A relatively severe turbulence environment at high altitude is quite credible because this element of Australia's flying occurs near the lattitude and altitude of the jet stream core, and predominantly over mountainous terrain. Therefore, it seems to me highly desirable to obtain more data for this altitude band.

3. THE RATIO OF UPGUSTS TO DOWNGUSTS

Following Bullen (1966) the ESDU data item 69023 has indicated that at low altitudes positive acceleration increments occur more frequently than negative increments. This is frequently attributed to the effect of manoeuvre loads (see, for example, Bullen, op. cit.). The ratio of upgusts to downgusts for the Australian data has been plotted in Figure 4, which parallels Figure 4 of the ESDU data item. The curve shown is computed by the expression

$$\frac{0{\cdot}85H + 9100}{H + 3300}$$

for altitudes, H (ft), less than 38,667 ft, and is taken as unity for greater altitudes. This curve is a close, but not exact, fit to the one shown in the ESDU data item. It can hardly be said that the data support the curve, but neither do they suggest any other curve.

4. THE VARIATION OF GUST FREQUENCY WITH GUST MAGNITUDE

Figures 5 and 6 show, for three different altitude bands, the frequency of occurrence of gusts of various magnitudes, relative to the number of times a 3 m/s gust is exceeded. The Figures parallel Figures 5 and 6 in the ESDU data item, and include the same design curves as the ESDU data item. Figure 5 shows the design curves for an aircraft not equipped with cloud warning radar whilst Figure 6 shows the design curves for an aircraft with cloud warning radar.

The data for the low altitude band (0–5000 ft) fall very close to the ESDU curve for aircraft without cloud warning radar. The greater part of these data was obtained from the Bristol Freighter and the TAA Viscount, none of which were equipped with radar, so it appears that this one of the ESDU design curves is well substantiated for Australian conditions.

The data for the medium altitude (15,000–20,000 ft) band come mainly from the Super Constellation and Viscount, neither of which were equipped with cloud warning radar. The high magnitude gusts appear to occur a little less frequently relative to the 3 m/s gusts than would be expected from the ESDU data curves. Several explanations are possible:

(*a*) Severe gusts tend to occur mainly in thunderstorms, which the Qantas Super Constellation had greater freedom to avoid near Australia than in the more congested skies of the northern hemisphere.

(*b*) Much of the data, being from the Super Constellation, may have been obtained from flights on a regular schedule which routinely passed through Australian air space at a time of day when thunderstorm activity was minimal.

(*c*) Much of the Super Constellation's data were from flights over the sea. The ESDU design curves indicate that terrain effects on the incidence of 3 m/s gusts are negligible above about 10,000 ft. It is possible, however, that the stronger gusts do show the effect of terrain to higher altitudes.

(*d*) Much of the Qantas flying is in low latitudes. There may be a latitudinal effect with strong gusts occurring relatively less frequently in tropical regions than in mid-latitudes.

(*e*) The differences may only be a result of the small data sample. About four times the distance was flown at mid-altitudes as at low altitudes, but since the expected number of gusts per unit distance is only 2% of what is expected at low altitudes, the expected number of gusts encountered at mid-altitudes is only 8% of that for low altitudes.

The data for the high altitude (30,000–40,000 ft) band are only available up to the 6 m/s level because of the relatively low incidence of turbulence at high altitudes. Such data as exist fall closer to the severe (no radar) design curve than to the milder (aircraft equipped with radar) design curve. This gives further weight to the opinion expressed, at the end of Section 2, that it is desirable to obtain more data for aircraft operating at high altitudes.

5. CONCLUSIONS

(1) Most of the flight data available are for scheduled passenger transport operations for which the Australia-wide incidence of turbulence can at best be defined to within a factor of about 3, and at many heights the uncertainty is much greater.

(2) From the Australian data it is not possible to make any distinction between types of flying (e.g. cruise, climb and descent or special missions) nor is there much information on the higher or lower incidence of turbulence to be expected in various regions of Australia.

(3) The available data are not incompatible with the ESDU data item 69023, except that at high altitudes (above 30,000 ft) there is some indication that turbulence is encountered more frequently than would be predicted by the ESDU design curves, and particularly so for the stronger gusts.

(4) A greater than average frequency of high altitude turbulence might be expected because the bulk of Australia's scheduled flying is in the Sydney–Canberra–Melbourne region where there is both a strong jet stream and a significant mountain range. This expectation reinforces the significance of the indications from the available data and so, in view of the paucity of data above 30,000 ft, it seems desirable to acquire more data at high altitudes.

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APPENDIX

A Summary of, and Comments on, the Data used in this Review

A.0 General

In order to bring all the data to a common basis, various calculations have been performed for each separate program as indicated in the later sections of the Appendix. A frequent problem was to interpolate tables of exceedances for gust velocities other than the measured values. This was done by assuming that between two measured values of gust velocity, the logarithm of the number of exceedances varied linearly with the gust velocity. A small degree of extrapolation was occasionally performed, usually by assuming that in a table of numbers of observed exceedances, the first zero value was replaced by 0·1.

There are certain observations which have been made many times before in connection with various programs of measurements of turbulence occurrence. They are reproduced here (in general without acknowledgement) because they carry a warning about how the data may be interpreted.

(*a*) The occurrence of turbulence is not simply an overall (space–time) atmospheric average because, in aircraft design or flight monitoring, it is the loads actually experienced by the aircraft which matter, and these depend on details of aircraft utilization (which may depend for example on the existence of weather radar or on the turbulence avoidance techniques used by the pilot). Several of the following observations are particularizations of this general one.

(*b*) Cruise conditions are generally less severe than climb and descent because, with some limitations, a pilot can choose a cruise-height of minimum turbulence.

(*c*) Initial climb and final descent are usually more severe than other climb and descent because, being generally in controlled air space, a pilot has less freedom in turbulence avoidance than in other locations.

(*d*) In some cases it has been suggested (Bullen 1966) that the decrease of gusts with altitude is related to the fact that pilots sometimes climbed to higher altitudes than they would otherwise have chosen in order to avoid turbulence.

(*e*) Counting accelerometer data have generally shown that at low altitudes upgusts occur more frequently than down gusts. This may be due to the presence of manoeuvres which are not distinguished from turbulence in counting accelerometer records. However, most of the manoeuvres made by transport aircraft appear sufficiently mild to not influence the number of significant loads. It is possible that the excess of updrafts is a genuine atmospheric phenomenon because, in convective fields, small concentrated updrafts tend to occur in a field of air which elsewhere is settling slowly and uniformly. There is, however, a problem still requiring explanation. Almost all of the early data (DC3, DC4 or Bristol Freighter) measured with V–g recorders in Australia (*see* Hooke 1956) show downgusts to be very much more frequent than upgusts.

(*f*) There is one source of difference between data from US gust measurements with with V–g–h recorders, and UK measurements with counting accelerometers which is additional to the other differences remarked on by Bullen (1958). Counting accelerometers are unable to distinguish between gusts and manoeuvres, but V–g–h recorders can, and in some cases (e.g. Hunter and Fetner 1967) the effect of manoeuvres has been removed from US gust data. With transport aircraft such as those summarised here, the effect is slight, but with smaller aircraft the differences may be considerable.

(*g*) Even fairly long samples of data may be influenced by regular scheduling, especially if certain routes are only flown once per day. For example, Bacon (1956) found a low incidence of turbulence on the Adelaide–Perth route which he attributed to the fact that the regular scheduled flight left Adelaide late in the afternoon and arrived at Perth in the evening. The return flight was early the next morning so several of the low altitude segments were flown near night time hours when turbulence might be expected to be low.

(*h*) Some minor variations between programs occur because in some cases conversion between acceleration and derived gust velocity is based on fixed average values of aircraft weight and lift-curve slope, whilst other more elaborate analyses allow for variations of these factors with height, velocity and time during the flight.

A.1 Bristol Freighter (ANA)

Reference: Baum and Hooke (1953)

The reference gives a table of occurrences of various acceleration ranges in 10 altitude bands. These were converted to exceedances of U_{de} using the following formula and parameter values:

$$U_{de} = \frac{2(W/S)}{\rho_0 V_e a F_0} \Delta n$$

U_{de} = Derived equivalent gust velocity
W = Aircraft weight
S = Wing area (1487 sq. ft)
W/S = 26·8 lb/sq. ft
ρ_0 = Sea-level air density (0·002378 slug/cu. ft)
V_e = Equivalent air speed (150 kn = 253 ft/sec)
a = Lift curve slope (4·4/rad)
F_0 = Gust alleviation factor obtained from Figure 7 of ESDU data item 69023 using the following additional data
$A\!\!\!/R$ = Aspect ratio (7·8)
μ = Mass parameter $[2(W/S)/g\rho a\bar{c}]$
$\bar{c}$ = Mean aerodynamic chord (13·8 ft)

For three different heights we obtain:

Height (ft)	ρ (slug/ft³)	μ	F_0	$U_{de}/\Delta n$ (ft/sec/g)
0	0·002378	11·5	0·67	30·2
5,000	0·002049	13·4	0·70	28·9
10,000	0·001756	15·6	0·73	27·7

For other heights the value of $U_{de}/\Delta n$ was interpolated linearly. The resultant table of gust velocity exceedances is shown as Table A1 at the end of this Appendix.

A.2 Viscount (TAA)

Reference: Bacon (1956)

The reference gives a graph (Fig. 1) of exceedances of various acceleration increments for cruise altitude. From this graph the exceedances of various gust velocities can be read off using the value of $U_{de}/\Delta n$ = 36 ft/sec/g given by Bullen (1966), and converted to exceedances per 1000 nautical miles for a true airspeed of 270 kn. The results are given in Table A2 at the end of this Appendix.

A.3 Bristol Freighter (SAFE, New Zealand)

Reference: Heath-Smith (1958)

The table of gust exceedances given in the reference was normalised (by dividing the numbers of exceedances by the distance flown) and a simple extrapolation (assuming the logarithm of the number of exceedances to vary linearly with the gust magnitude) was carried out to obtain the exceedances of the innermost levels. The result is given as Table A3.

A.4 Super Constellation (Australia)

A.5 Super Constellation (Indian Ocean)

A.6 Super Constellation (Far East)

A.7 Super Constellation (Pacific Ocean)

Reference: Heath-Smith (1959)

The gust exceedances in the above four regions have been tabulated in the reference. After division by distance flown they have been listed in Tables A4 to A7 at the end of this Appendix.

A.8 Viscount (TAA)

Reference: Visick (1965)

The reference gives a table of gust occurrences in 4 ft/sec gust velocity bands. This table was integrated and interpolated to give the table of gust exceedances shown as Table A8 at the end of this Appendix.

A.9 Canberra (TOPCAT)

Reference: Bullen (1966)

Bullen (1966) quoting Wells (1966), gives a table of exceedances of gusts for routine search flights at 36,000 ft in the TOPCAT project. The relevant results are repated in Table A9.

A.10 Boeing 727 (Ansett)

A.11 Boeing 727 (TAA)

Reference: Hunter and Fetner (1967)

Hunter and Fetner show a table of gust occurrences in 4 ft/sec bands of gust velocity. The calculation of gust velocity follows the American practice using the Pratt and Walker gust alleviation factor and an old formula for the lift curve slope. To make the data compatible with the other data presented in this report the gust velocities were factored by various amounts, as shown in the table below. At the same time the wing lift curve slope was recalculated using the USAF stability and control DATCOM procedure. (NTIS Accession Number N76-73204.) The data used and the resultant values of U_{de}/g are shown below:

$$W = 57{,}652 \text{ kg}$$
$$S = 148 \cdot 5 \text{ m}^2$$
$$\bar{c} = 4 \cdot 32 \text{ m}$$
$$AR = 7 \cdot 5$$
Leading edge sweepback $= 36°$
Mid-chord sweepback $= 27°$
Section lift curve slope $= 0 \cdot 95 * 2\pi$
Wing thickness $= 11\%$ chord

Height (ft)	CAS		Hunter and Fetner		British method	
	kn	m/s	a (per rad)	U_{de}/g (m/s)	a (per rad)	U_{de}/g (m/s)
2,500	185	95	4·38	19·48	4·37	18·49
7,500	304	156	4·67	11·01	4·67	10·69
12,500	324	167	4·84	9·8	4·85	9·62
17,500	332	171	5·02	9·1	5·04	9·01
22,500	336	173	5·28	8·46	5·29	8·48
27,500	324	167	5·48	8·36	5·48	8·44
32,500	303	156	5·63	8·60	5·61	8·75
37,500	282	145	5·82	8·88	4·37	11·78

In fact the two calculations of gust velocity per unit acceleration increment give very similar values. The biggest difference (at the highest altitude) happened mainly because the Mach number was near the force break Mach number and the older formula for the lift curve slope did not allow for this. After the necessary corrections and interpolations the tables of gust velocity exceedances were obtained as shown in Tables A10 and A11.

TABLE A.1

Aircraft: Bristol Freighter   Reference: Baum and Hooke (195?)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
500–1500	Climb, Cruise, Descent all combined	785						2·01	14·0	46·6	443	1632	296	43·3	15·1	3·24	1·27	0·18		
1500–2500		1163			0·108	0·765	0·860	3·04	10·5	37·6	270	1034	172	35·2	10·9	3·58	1·48	0·12		
2500–3500		1204						0·64	4·65	17·3	127	495	70·6	11·2	0·64					
3500–4500		1307						0·272	2·30	12·5	93·3	369	46·2	5·6	0·28					
4500–5500		2295						0·155	0·436	4·44	31·6	108	14·0	2·30	0·16					
5500–6500		2105							0·90	5·32	36·2	139	8·88	0·52						
6500–7500		2087							0·24	1·77	16·1	58·9	6·04	0·24						
7500–8500		1587								0·56	6·55	22·0	3·28	0·32						
8500–9500		2093									1·48	11·1	0·16							
9500–10500		870								0·63	29·8	110	6	0·46						

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.2

Aircraft: Viscount (TAA)   Reference: Bacon (1956)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
17000–22000	C	23760				0·037	0·111	0·333	1·074	3·148	—	—	2·037	0·815	0·241	0·130				

Note: C = Cruise;
CD = Climb and Descent.

TABLE A.3

Aircraft: Bristol Freighter (New Zealand)   Reference: Heath-Smith (1958)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–1500	CD	2591	—	0·166	0·166	0·331	0·496	4·13	21·19	139	1016	2245	379·4	56·39	9·919	1·985	0·166	—	—	—
1500–3500	CD	3455		0·166	0·166	0·331	0·496	4·13	21·16	139	1016	2245	379	56·4	9·92	1·985	0·166			
0–1500	CD	4237		0·236	0·236	0·472	0·944	3·54	17·9	107	541	2385	386	55·9	11·8	3·068	1·180	0·708	0·472	0·236
1500–3500	CD	2907					0·344	3·44	14·1	88·8	445	1289	222·6	35·8	5·85	1·72	0·668			
3500–5500	CD	1434						2·79	11·16	43·2	243	461	66·9	10·5	2·09					
5500–11500	CD	531						1·883	5·65	20·7	125	153	7·53							
0–1500	C	30268				0·066	0·231	0·892	5·68	49·7	411	1172	118	12·26	1·718	0·297	0·066			
1500–3500	C	18942				0·053	0·106	0·95	6·39	37·3	254	717	98·1	11·61	2·27	0·581	0·211	0·106		
3500–5500	C	9648						0·311	4·664	31·8	230	464	57·32	7·359	1·658	0·518	0·311	0·104		
5500–11500	C	6139				0·163	0·326	1·466	3·747	16·78	111	125·7	14·82	4·887	0·439					

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.4

Aircraft: Super Constellation   Reference: Heath-Smith (1959)—Australian Region

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–1500	CD	292					3·425	17·1	51·4	161	—	—	384	85·6	37·67	10·27				
1500–3500	CD	1405					0·712	2·135	10·7	51·2	—	—	102	14·9	4·27	2·85	2·135	1·423	1·423	0·712
3500–5500	CD	1136					0·88	4·401	14·97	53·7	—	—	126·8	20·25	6·162	3·521	0·88			
5500–9500	CD	2977					1·008	3·023	7·39	23·85	—	—	65·17	13·1	2·687	1·008	0·336	0·336		
9500–13500	C	25822						0·194	1·007	7·01	—	—	10·88	0·929	0·194					
13500–17500	C	53500					0·019	0·637	0·299	1·925	—	—	4·093	0·374	0·056					
17500–21500	C	20407				0·098	0·245	0·833	2·156	11·075	—	—	10·63	1·813	0·49	0·098				

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.5

Aircraft: Super Constellation   Reference: Heath-Smith (1959)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–1500	CD	371				2·695	2·695	2·695	13·5	113	—	—	410	72·8	8·086	2·695				
1500–3500	CD	1812							4·415	26·49	—	—	68·4	9·38	2·21	0·55				
3500–5500	CD	1447							2·07	20·04	—	—	38·71	2·764	1·382	0·691				
5500–9500	CD	3221				0·621	0·931	1·24	2·79	6·83	—	—	9·935	2·794	1·552	1·552	0·621			
9500–13500	C	25964						0·193	0·578	2·349	—	—	2·735	0·424	0·154					
13500–17500	C	63486				0·063	0·173	0·347	0·725	2·678	—	—	4·458	1·024	0·378	0·110	0·032	0·016		
17500–21500	C	13948						0·430	1·147	1·434	—	—	1·219	0·143	0·072					

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.6

Aircrfat: Super Constellation Reference: Heath-Smith (1959)—Far East

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–1500	CD	818						1·222	12·23	84·4	—	—	268	46·46	8·557	1·222	1·222			
1500–3500	CD	3552					0·282	0·845	4·223	23·09	—	—	99·38	11·82	1·971	0·282				
3500–5500	CD	3802							1·578	10·78	—	—	27·09	3·68	0·263					
5500–9500	CD	7077		0·141	0·141	0·141	0·283	0·848	2·967	12·86	—	—	16·53	2·967	0·707	0·283	0·283	0·141	0·141	
9500–13500	C	29147			0·034	0·172	0·240	0·618	1·853	7·376	—	—	11·39	1·510	0·343	0·103				
13500–17500	C	108780	0·018	0·018	0·018	0·037	0·064	0·211	0·634	2·234	—	—	3·732	0·689	0·184	0·046	0·009			
17500–21500	C	16068		0·062	0·062	0·124	0·187	0·436	1·120	3·112	—	—	5·726	1·058	0·498	0·311	0·124			

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.7

Aircraft: Super Constellation   Reference: Heath-Smith (1959)—Pacific Ocean

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–1500	CD	1004					0·996	6·972	24·9	107·6	—	—	286	36·85	10·96	1·992				
1500–3500	CD	3823					0·262	0·785	6·278	33·48	—	—	88·151	13·08	2 616	1·046				
3500–5500	CD	4348					0·23	1·1[illegible]	2·99	22·31	—	—	40·02	8·05	2·76	1·15				
5500–9500	CD	11202					0·357	[illegible]	4·463	18·39	—	—	28·21	4·999	1·25	0·446				
9500–13500	C	148236		0·007	0·02	0·034	0·169	0·587	1·194	5·323	—	—	6·186	1·268	0·506	0·148	0·034	0·007		
13500–17500	C	116107			0·017	0·034	0·095	0·284	0·698	2·928	—	—	3·945	0·637	0·25	0·121	0·026			
17500–21500	C	4201					0·238	0·476	1·428	4·523	—	—	9·045	1·666	0·476	0·238				

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.8

Aircraft: Viscount (TAA) Reference: Visick (1965)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–2500	C	5751				0·095	0·592	2·052	7·296	39·22	—	—	108·3	23·49	6·182	0·883	0·056			
2500–7500	C	737							0·882	3·51	—	—	8·00	1·003						
7500–12500	C	3996						0·196	0·738	3·674	—	—	5·451	0·529	0·096					
12500–17500	C	14877					0·033	0·067	0·132	0·958	—	—	0·924	0·088	0·019					
17500–22500	C	89910			0·005	0·011	0·016	0·041	0·121	0·804	—	—	1·291	0·26	0·055	0·019	0·006			
22500–27500	C	13500								0·218	—	—	0·602	0·147	0·026					
0–2500	CD	7992			0·014	0·15	0·68	2·56	12·79	54·9	—	—	97·63	25·16	5·89	1·315	0·278	0·128	0·056	
2500–7500	CD	15120				0·038	0·155	1·033	4·476	23·03	—	—	36·81	7·788	1·378	0·165	0·038			
7500–12500	CD	14472						0·056	0·464	3·833	—	—	5·303	0·713	0·115					
12500–17500	CD	15417						0·100	0·648	3·809	—	—	3·843	0·606	0·081					
17500–22500	CD	3672								4·94	—	—	5·582	1·376	0·33					

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.9

Aircraft: Canberra   Reference: Wells (1966)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
about 36000	C	7355										55·6	1·903							

Note: Exceedances of upgusts and downgusts combined

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.10

Aircraft: Boeing 727 (Ansett) Reference: Hunter and Fetner (1967)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–5000	Climb, Cruise, Descent all combined	8252	—	—	—	—	—	—	—	—	—	—	5502	20·51	4·66	0·98	0·14	0·12		
5000–10000		6093	—	—	—	—	—	—	—	—	—	—	22·46	3·57	0·21					
10000–15000		6327	—	—	—	—	—	—	—	—	—	—	10·44	0·92	0·24					
15000–20000		6851	—	—	—	—	—	—	—	—	—	—	4·76	1·18	0·28	0·15				
20000–25000		8857	—	—	—	—	—	—	—	—	—	—	3·85	0·21	0·11					
25000–30000		18453	—	—	—	—	—	—	—	—	—	—	1·123	0·016						
30000–35000		44798	—	—	—	—	—	—	—	—	—	—	3·45	0·614	0·124					
35000–40000		2372	—	—	—	—	—	—	—	—	—	—	0							

Note: Exceedances of upgusts and downgusts combined

* Note: C = Cruise;
CD = Climb and Descent.

TABLE A.11

Aircraft: Boeing 727 (TAA) Reference: Hunter and Fetner (1967)

Altitude band (ft)	C* CD	Nautical miles	Number of exceedances per 1000 nautical miles of U_{de} (m/s)																	
			−13·5	−12·0	−10·5	−9·0	−7·5	−6·0	−4·5	−3·0	−1·5	1·5	3·0	4·5	6·0	7·5	9·0	10·5	12·0	13·5
0–5000	Climb, Cruise, Descent all combined	5957	—	—	—	—	—	—	—	—	—	—	50·74	14·67	1·81	0·058				
5000–10000		4370	—	—	—	—	—	—	—	—	—	—	13·18	1·72	0·29					
10000–15000		4463	—	—	—	—	—	—	—	—	—	—	3·65	0·05						
15000–20000		4524	—	—	—	—	—	—	—	—	—	—	1·17	0·045						
20000–25000		5628	—	—	—	—	—	—	—	—	—	—	0·163							
25000–30000		9906	—	—	—	—	—	—	—	—	—	—	2·65	0·817	0·213	0·202	0·202	0·202	0·108	
30000–35000		35815	—	—	—	—	—	—	—	—	—	—	0·156	0·006						
35000–40000		2961	—	—	—	—	—	—	—	—	—	—	1·869							

Note: Exceedances of upgusts and downgusts combined

* Note: C = Cruise;
CD = Climb and Descent.

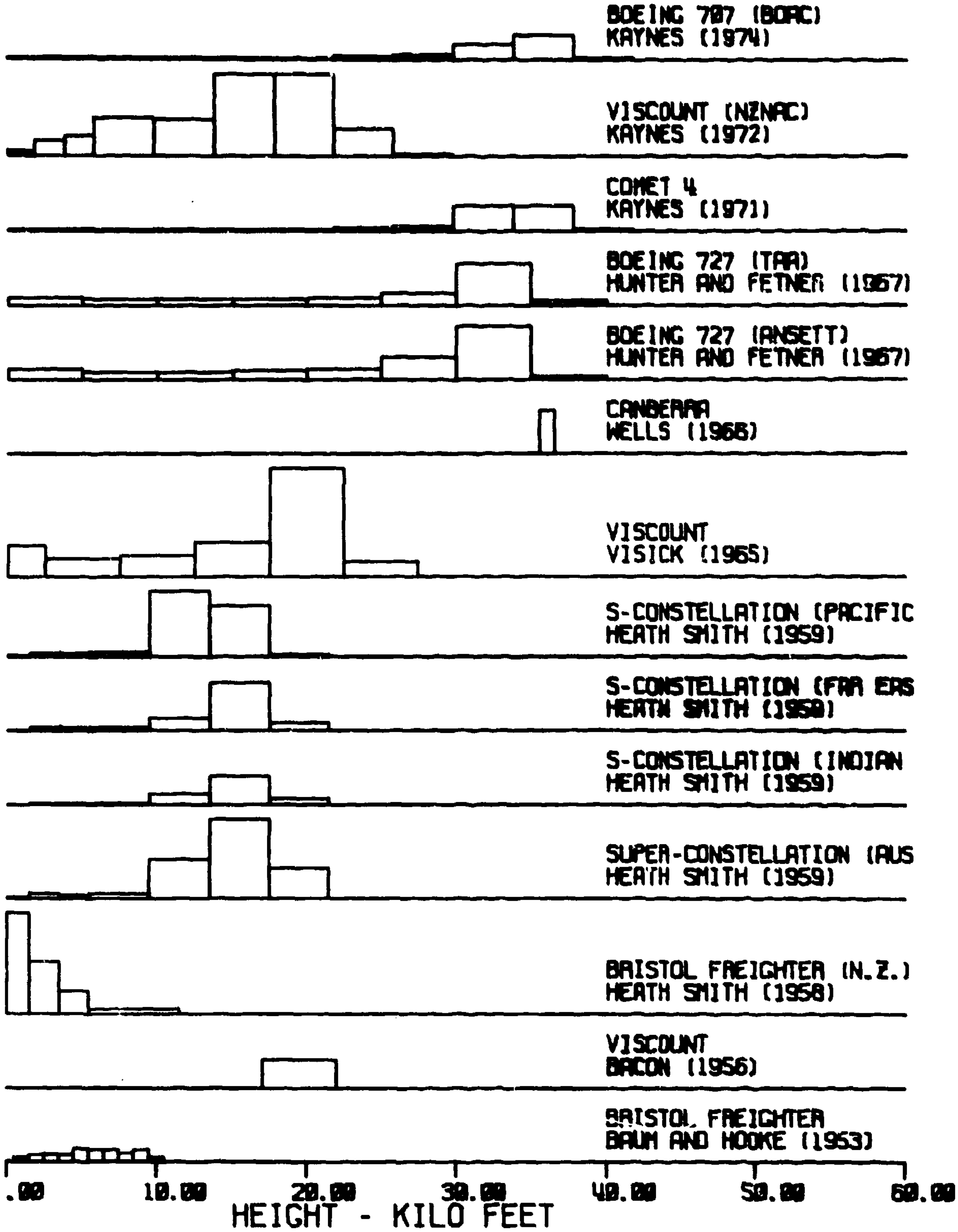

FIG. 1 QUANTITY OF DATA AVAILABLE AT VARIOUS ALTITUDES FROM THE VARIOUS MEASUREMENT PROGRAMMES.
(The area of each rectangle is proportional to a weighting factor (shown in Table 1) multiplied by the distance flown in the height band.)

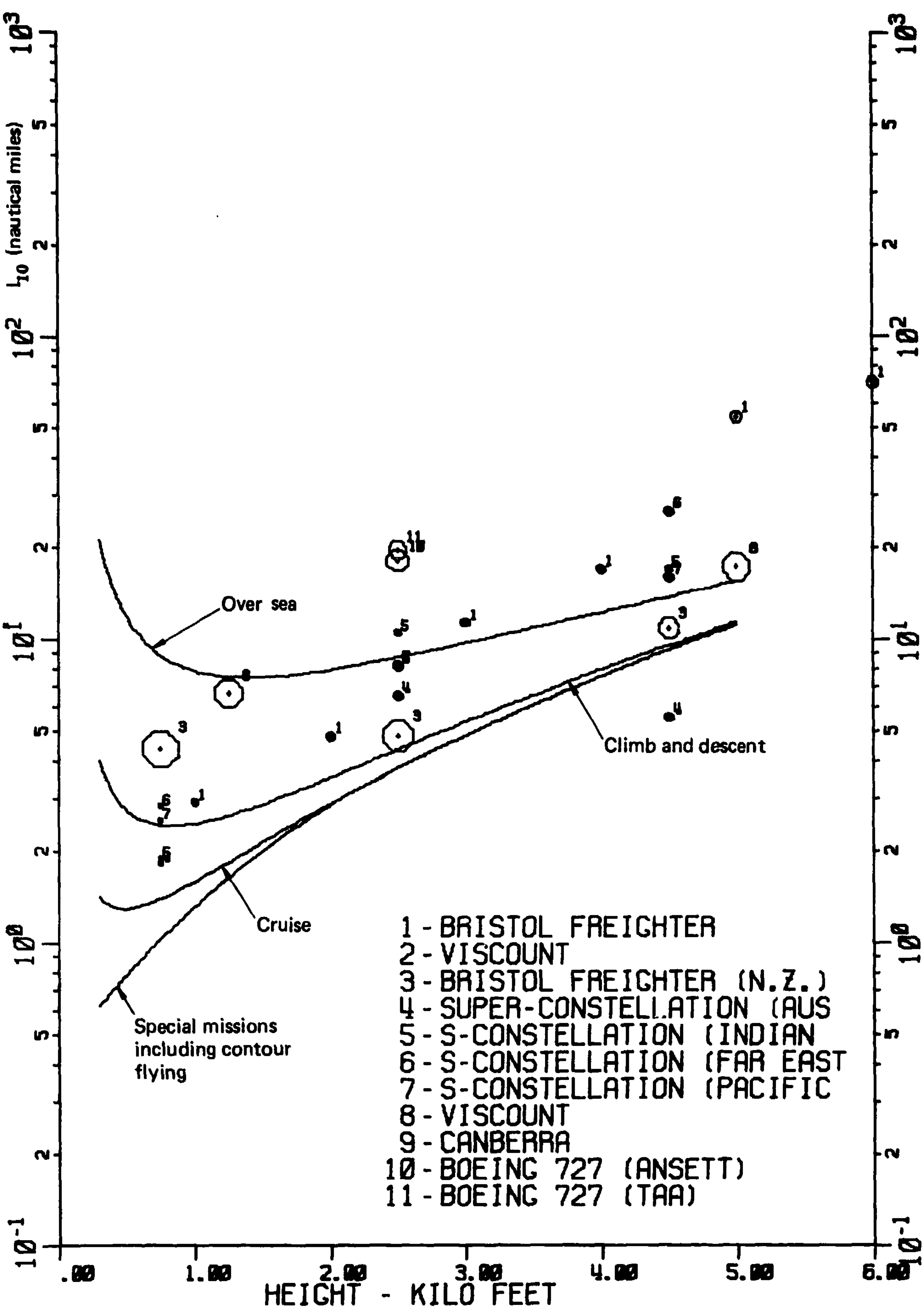

FIG. 2 VARIATION OF L_{10} WITH ALTITUDE.
Australian data compared with ESDU design curves

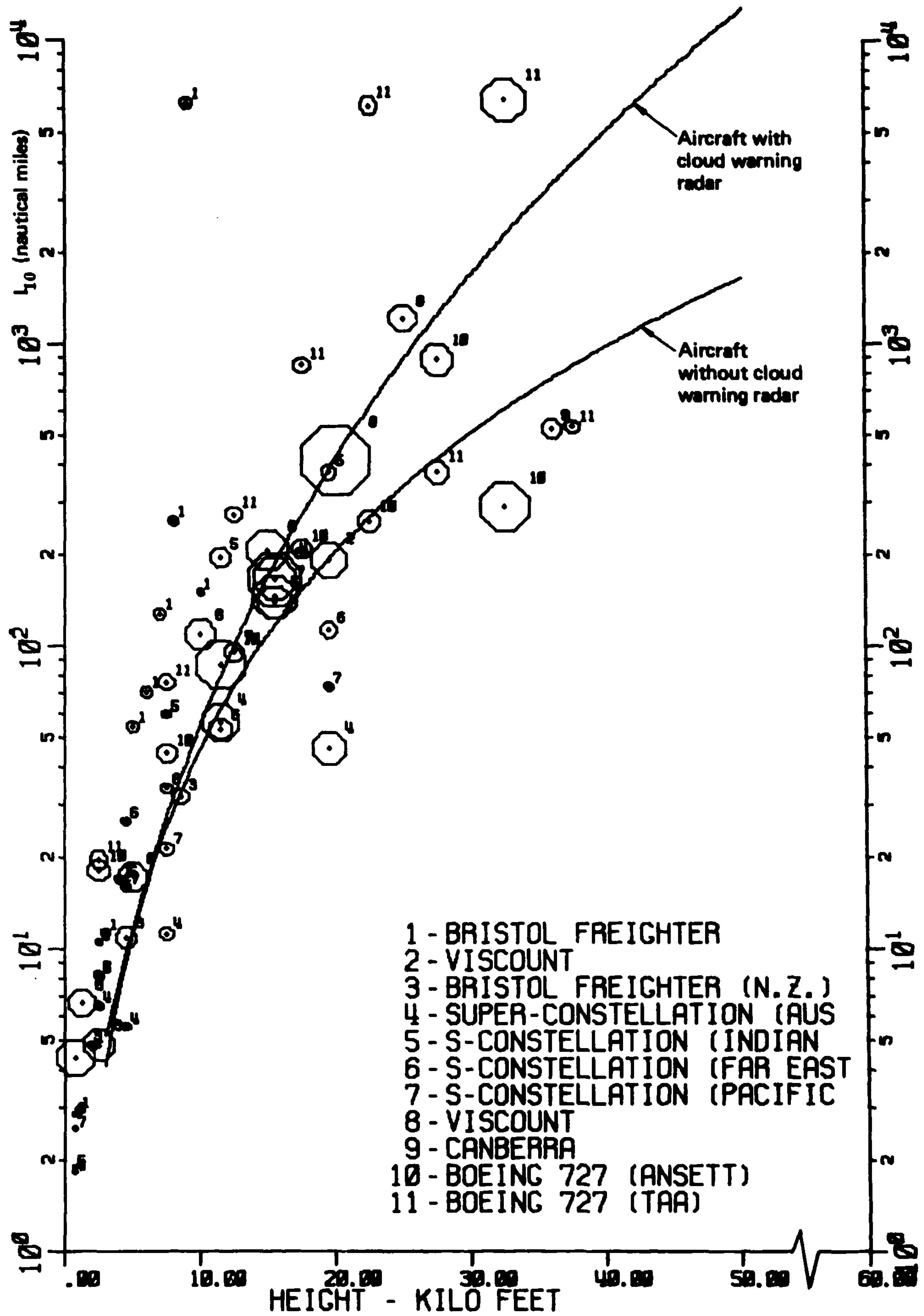

FIG. 3 VARIATION OF L_{10} WITH ALTITUDE
Australian data compared with ESDU design curve

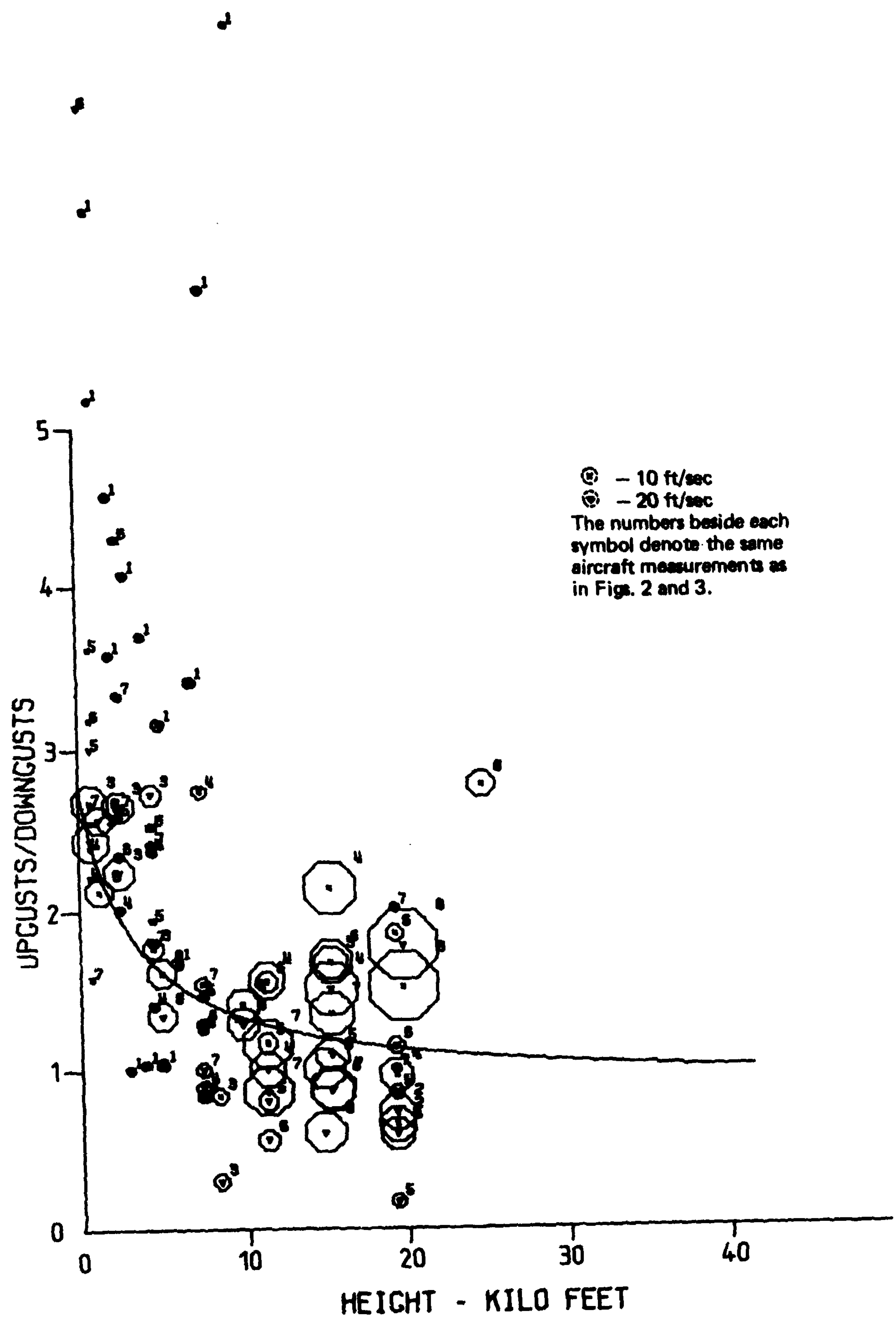

FIG. 4 RATIO OF UPGUSTS TO DOWNGUSTS
Australian data compared with ESDU design curve

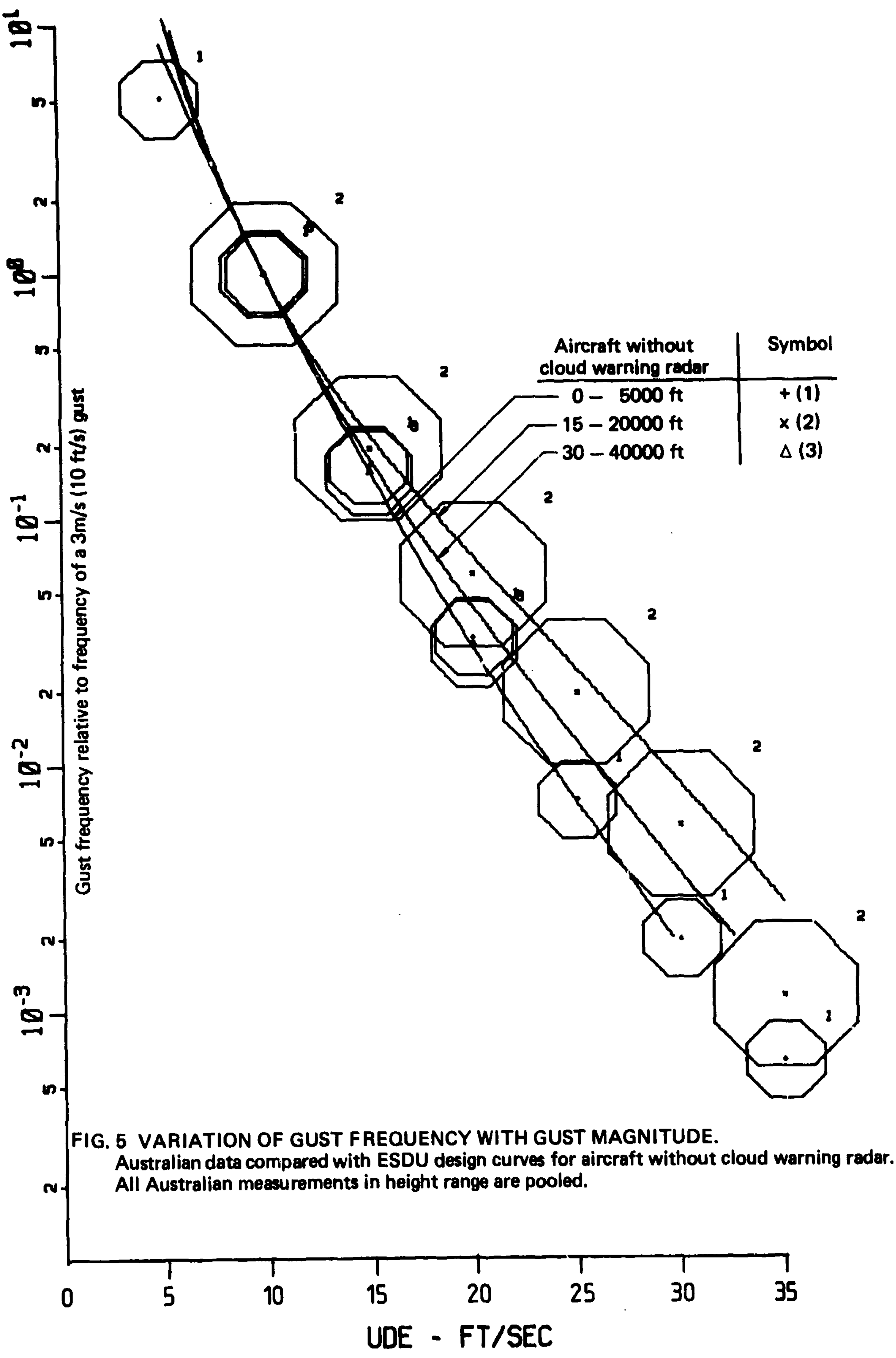

FIG. 5 VARIATION OF GUST FREQUENCY WITH GUST MAGNITUDE.
Australian data compared with ESDU design curves for aircraft without cloud warning radar.
All Australian measurements in height range are pooled.

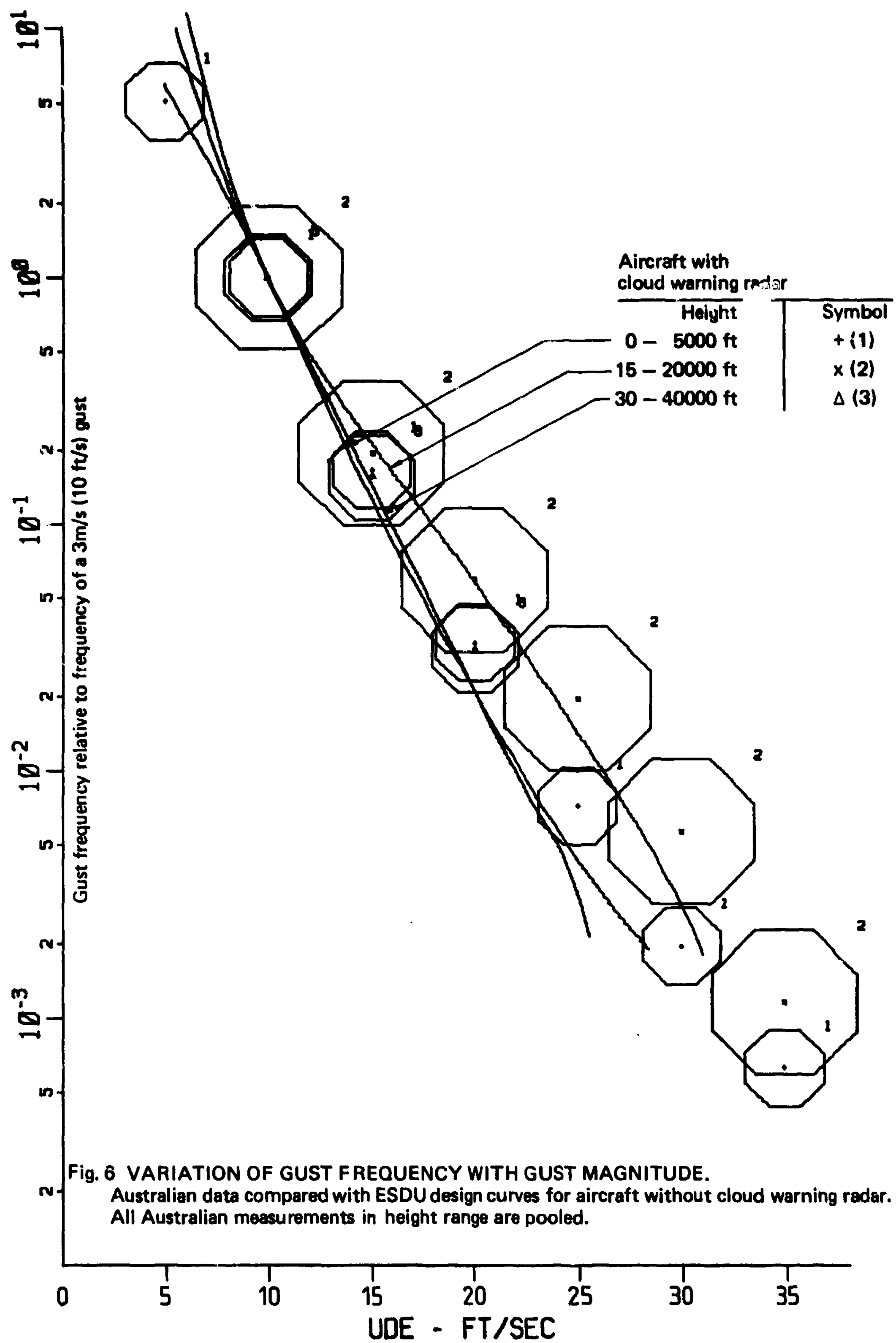

Fig. 6 VARIATION OF GUST FREQUENCY WITH GUST MAGNITUDE.
Australian data compared with ESDU design curves for aircraft without cloud warning radar.
All Australian measurements in height range are pooled.

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